Elevate: A Walkable Pin-Array for Large Shape-Changing Terrains

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ABSTRACT

Current head-mounted displays enable users to explore virtual worlds by simply walking through them (i.e., real-walking VR). This led researchers to create haptic displays that can also simulate different types of elevation shapes. However, existing shape-changing floors are limited by their tabletop scale or the coarse resolution of the terrains they can display due to the limited number of actuators and low vertical resolution. To tackle this challenge, we introduce Elevate, a dynamic and walkable pin-array floor on which users can experience not only large variations in shapes but also the details of the underlying terrain. Our system achieves this by packing 1200 pins arranged on a 1.80 × 0.60m platform, in which each pin can be actuated to one of ten height levels (resolution: 15mm/level). To demonstrate its applicability, we present our haptic floor combined with four walkable applications and a user study that reported increased realism and enjoyment.

CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**.

KEYWORDS

Haptic Floor, Shape Changing Display, VR

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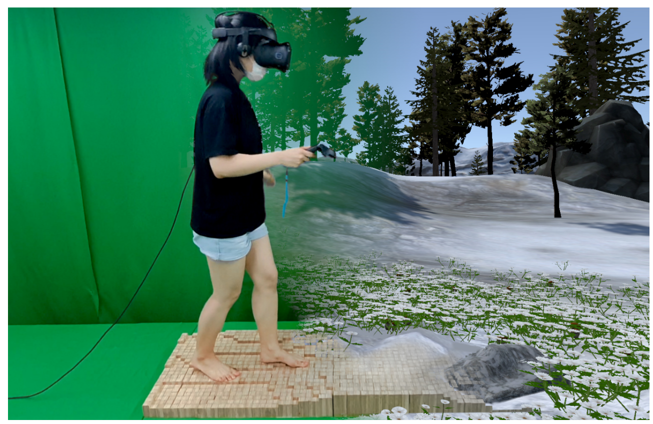

Figure 1: Elevate is a walkable high-resolution and large-scale pin-array display that can generate a variety of physical terrains for virtual reality. Here, we demonstrate our device generating the terrain of a landscape and a user walking on it.

1 INTRODUCTION

Today, the majority of head-mounted displays, even most commercial devices, allow users to explore virtual worlds by simply walking around in their surroundings; this is known as *real-walking Virtual Reality* (VR). The advantage of real-walking VR as a locomotion modality is that it is immersive as it stimulates the user's proprioceptive and vestibular senses as users physically move their bodies both in the real and virtual environments. This compelled researchers into tackling a subsequent key challenge that arises in real-walking VR systems: not only should users be able to walk around but also they should *be able to feel the terrain beneath their feet* (e.g.,[18, 23, 27]).

In fact, although often taken for granted, walking is a rich somatosensory activity, all the way down from limb movements to the feedback we feel from the soles of our feet. The body is capable of perceiving the slightest variation in inclination, bumps, and holes in the terrain, with the feet serving simultaneously as kinesthetic [23] and tactile [44] sensors. Different from the hands, the static and dynamic forces applied to the feet during standing or walking are in the order of hundreds or thousands of Newtons [44], making the experience of "feeling through the feet" a unique yet powerful haptic experience.

The search for this elusive haptics for feet, led researchers into engineering haptic devices that can render terrains by physically displacing modular pieces that the user stands on, such as moving robot tiles [10], tilting haptic tiles [1, 2, 5], inflatable airbags [36, 40], tilt-adjustable treadmills [24], and pin-arrays [33]. However, these previous shape-changing floors are limited by their tabletop scale [1, 2, 5] or the coarse resolution of the terrains they can display, due to the limited number of actuators [2, 10, 24, 33, 36, 40] and their low vertical resolution [2, 24, 40].

To tackle these challenges altogether and contribute to the field of interactive haptics, we introduce *Elevate*, a dynamic and walkable pin array floor on which users can not only experience large variations in shapes but also subtle details of the underlying terrain, as depicted in Figure 1. Our device achieves this by means of 1200 individually controllable pins arranged on a 1.80m × 0.60m platform. Furthermore, each 3cm × 3cm size pin can be actuated to one of ten height levels (resolution: 15mm/level). To illustrate the design space enabled by this one-of-a-kind large-scale haptic floor, we present it in combination with several real-walking VR and standalone applications. Lastly, we validated our prototype through a user study in VR, in which participants reported increased realism and enjoyment when experiencing the VR environment via Elevate.

2 RELATED WORK

The work we present in our paper builds on the fields of haptics, especially on hardware-techniques that deliver haptics to the user's feet, not only for virtual-reality but also for more general interactive walking experiences.

2.1 Foot-based Haptics

Kinesthetic and tactile feedback through one's feet, such as elicited when walking [23, 44] in virtual reality, is an important factor for attaining immersion in virtual environments or creating rich interactive experiences. To achieve this, researchers have developed a number of wearable devices that deliver foot haptic feedback to the user's feet. One such approach is to create "haptic shoes", i.e., shoe-like interfaces, embedded with haptic actuators, that users wear as they walk around. For instance, Turchet et al. [41] and Takeuchi [38] attached vibration actuators on the sole of the shoes to provide a walking experience on virtual ground. Hill et al.[7] also explored transferring information by using vibration actuators. RealWalk [32] adopted actuated MR fluid to express the deformation of materials on the ground in VR, such as snow, sand and mud. Wang et al. [46] developed air-bladder-based elastomeric shoes to express the slope of the ground. Level-Ups [28] is a pair of mechanical brake-actuated shoes that can simulate different heights of a virtual terrain. Although wearable foot haptic devices have the benefit of working over a larger (potentially infinite) area, they require instrumenting the user's feet, which results in reduced comfort.

Another well-researched approach for delivering haptics to the user's feet is to let users stand on a platform embedded with haptic feedback. Visell et al. [42, 43] used vibrators and spring mechanisms [44] to provide the feeling of walking over snow or sand, i.e., achieving ground textures. Wohlauf et al. [47] introduced the haptic tile, which works as a weight scale on which users have a sense of load with rigidity instead of the numeric weight value. Also, researchers have explored adding tangible objects, which the users can kick around to control their interface, on top of interactive floors [29].

Haptic floors are of especial importance for real-walking VR because, in this type of setups, the user is *already* bounded to the tracking volume and thus the aforementioned advantages of haptic shoes become less pronounced. As such, researchers have long explored robotic walking simulators [11, 30] and robot tiles, which can move up/down, allowing users to walk over different heights. The more recent approach, is to directly manipulate the terrain by employing motor-actuated tiles (i.e., a tile is a modular segment of the whole floor, typically in a grid layout), such as by manipulating the tile's adjustable slope [2, 5], using a turntable with a slanting mechanism [1], or even using adjustable incline treadmills [8, 9]. For example, the *Ground Surface Simulator* [24] is a treadmill featuring six linear actuators that together create various slopes on which the user can walk on. However, in these types of haptic devices, the expressiveness of terrain detail felt by the feet is limited as their resolutions are very coarse, i.e., each tile is very large. Elevate, on the other hand, renders both the topology of a landscape and its non-linear slope while intentionally avoiding user's instrumentation which causes discomfort to the users.

2.2 Pin-array Displays

Shape displays [6, 12, 14–16, 25, 31, 37, 50, 51] provide a higher resolution implementation of the aforementioned actuated-"tiled" approach, allowing to display physical 2.5D shapes with high resolution. However, most shape displays are designed as a tabletop interface for interactions with the hands and arms [6, 15, 16, 31, 37, 50, 51]. These shape displays are often implemented via a 2D array of pin actuators, with each pin being moved independently by a motor, typically a linear actuator as in [6, 15, 16, 31, 37, 50]. The result is high resolution with, typically, fast update speeds. However, the limiting factor is that these linear actuators cannot withstand hundreds of kilograms of force, i.e., users can touch them with their hands but cannot stand or walk on them.

Our device takes inspiration from these aforementioned pin-based shape-changing tabletops but aims at redesigning their inner workings to enable foot-based haptic feedback, aiming for a large scale device that covers a sufficient arena and withstands a user's weight as they walk on the device.

In fact, other researchers have recently explored the idea of generating different terrains using push-pull mechanisms, such as pneumatic actuators [36, 40], or mechanical linear actuators [2, 24, 33] installed on a platform. For instance, both TilePoP [40] and LiftTiles [36] are haptic floors that use pneumatic actuators as an approach to scale up in one dimension to display virtual objects. Yet, these platforms are of coarse resolution, and inflated actuators are not stable enough for any user to walk on, as researchers have highlighted in their findings [36, 40]. Moreover, researchers have built haptic floors that generate terrains, such as the ALF (ALive

Floor) [33]. ALF has 28 pin actuators with eight triangulated panels on each actuator. However, this device, much like those of [40] and [36], is limited to low-resolution feedback, not quite capable of generating terrains with high-resolution, e.g., they can elevate the user's feet but cannot generate a sharp incline or the feeling of standing on textures and uneven ground (i.e., rocky ground). Instead, Elevate bridges between these trade-offs, by proposing a walkable large-scale and high-resolution shape changing pin-array display that can render a variety of physical terrains with a finite number of actuators.

3 FOUR KEY CHARACTERISTICS OF HOW ELEVATE CREATES WALKABLE DYNAMIC TERRAINS

To give the reader a complete picture of how Elevate creates walkable dynamic terrains, we describe an example walkthrough of a user experiencing a rocky desert in virtual reality (VR).

As shown in Figure 2, the user is crossing a rocky VR desert, but the path is cut off by a canyon. To cross over the canyon, the user picks up some nearby rocks and drops them into the canyon. After throwing enough rocks, these start to pile up into a pillar that stands out. As a response, Elevate creates a *physical* pillar by moving its pins upwards. Because the elevation created by our device is stable, due to its strong locking mechanism, the user can cross the canyon by *physically stepping on the pillars*. This depicts two among four key characteristics of our design: **(1) it withstands human weights**; and, **(2) its feedback is dynamic**, i.e., it can re-configure any pin that the user is not standing on at run-time.

Figure 2: As the user fills the bottom of the cliff with rocks, Elevate dynamically creates pillars that match the shape of the rocks. These pillars are sturdy enough that the user can walk on them to cross the canyon.

Then, on the other side of the canyon, the user encounters a rocky fields for which is finding a way through is difficult. As the user keeps walking (Figure 3 (a)), the user is able to feel the terrain underneath. This showcases Elevate's third key characteristic: **(3) its a large walkable surface of 1.8 x 0.6 m**, longer and wider than the typical haptic floor [2, 5], and compatible with the explored surface area used for VR applications [33].

Finally, the user finds a way out of the desert by stepping over several rocks of different shapes and sizes, which our device generates accordingly as depicted in Figure 3 (b)– the user feels each rock's shape and size at each step. This is only possible due to our fourth key principle: **(4) unprecedented resolution of 1,200 pins, each covering an area of 3 x 3 cm in a 20 x 60 grid**. Our pins can also rise up to 15mm, with 10 discrete intermediate positions (15 mm vertical resolution). This level of detail, seen before only on tabletop pin-array displays [6, 15, 16], is what allows to depict the fine-grained differences between the rocks displayed in Figure 3 (c-f).

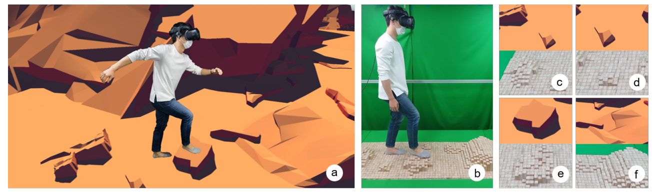

Figure 3: (a) As the user keeps walking in this VR desert, the feet keep experiencing tactile feedback over a haptic large-area of 1.8 x 0.6 m; (b) Here, the user feels the shape of a rock under the feet. (c-f) Elevate makes use of its high vertical and horizontal resolution to render the different shapes of the different rocks the user steps on.

In summary, compared to previous haptic floors, Elevate provides unique physical affordances that allow to realize new and unforeseen applications at a larger scale. While we demonstrated the four benefits of Elevate (i.e., withstands human weight, dynamic, large scale, and high-resolution) in the example of this VR walkthrough, in the Applications section we will also showcase how Elevate enables new interactive scenarios outside of VR.

4 SYSTEM IMPLEMENTATION

Elevate is made of three components: 1200 pins, a shape generator (the electromechanical device that moves the pins), and a locking system (the electromechanical device that secures the pins in place) (Figure 4). Generally speaking, the mechanical principle behind Elevate is as follows: (1) its pins are actuated by the motorized shape generator one row at a time, allowing them to take the shape of the intended terrain; (2) what keeps the pins from falling back down are strong magnets that temporarily hold the pins in place at a desired height while a single row is being rendered; (3) then, when a particular row is updated (i.e., all pins of this row have been set at their intended height), the pins are firmly locked using our motorized brake mechanism; lastly, (4) after locking any row of pin, the user can walk over these.

Elevate is mounted on a box-framed structure made from aluminium profiles (120 cm wide x 248 cm deep x 73 cm high). The top side of the box (at 73 cm) is our actuated platform, and it is covered by a smooth sheet of birch plywood (15T), which houses the pins and prevents them from colliding with each other. In the middle, there is a layered structure made of an acrylic sheet (6T) and of an iron plate (14T) glued together. All these elements combined make up for a strong platform that bears the weight of an average user.

Furthermore, the side of the box structure also has attachments for protective railings that prevent users from falling down from the platform. The following subsections describe the implementation details of the three main components of Elevate and how they communicate with each other.

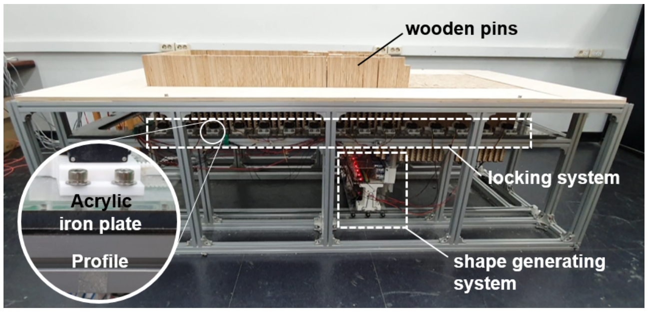

Figure 4: Three major components of Elevate: (1) the pins (top); (2) its locking system (middle), and (3) its shape generator (lower). We depict also a detail of how we layered the materials in Elevate's mid supporting structure.

4.1 Pins

Each of the 1200 pins of Elevate was machined from a block of birch plywood and shaped to support a 150 mm vertical displacement. The cuboid shape of the pins was designed by referring to previous studies [6, 15, 16] and taking into account two requirements: density (no hole between the pins) and the need to operate the pins line by line (using the shape generator). The pin mainly consists of three parts. The top part of the pin is a solid block of 195 mm with a 30 mm × 30 mm section that can protrude from the platform. This is the part of the pin that has to support the user's weight and therefore is completely filled to avoid deformations from compression. The lower part is a comb-shape section with 24 notches. Half of these are larger and are used in combination with the locking system — specifically, an aluminium bar that prevents vertical translations (see detailed explanation in locking system). These large notches have a pitch of 15 mm, resulting in the pin's vertical resolution of 150 mm. The remaining notches are smaller and contains 12 permanent neodymium magnets (15 mm × 10 mm × 4 mm, of strength 3100 G) which are used to temporarily keep the pin lifted in the desired height level before the locks are inserted into the notches. Finally, the bottom side of the pin is fixed with a metal iron plate (18 mm × 19 mm × 4 mm) which protects the pin from impacts with the shape generator, and serves a magnetizable surface for pulling the pin down. In total, the system contains 1200 wooden pins with 14,400 magnets and 1200 metal plates, for a cumulative weight of 240 Kg (200 g per pin).

4.2 Shape generator

The shape generator is the core of the system. Its purpose is to individually push or pull each of the 1200 pins, rendering various types of terrains and features. The main challenge is to minimize the number of actuators needed to individually control the height of each of the pins. We achieve this by using a shape generator that moves row by row on a rail underneath the pins platform, and pushes or pulls at the same time all the pins on the same row.

The horizontal movement is generated using a pair of aluminum timing belts (GT2, 36 teeth, 6 mm) attached to a system of pulleys. Pulleys are driven by two coaxial stepper motors (A15K-S545-G10 with 0.75 A/Phase) using a set of micro-stepper drivers (MD5-HD14) and powered by a single 24 V power supply at 4.5 A. A switch is placed at one end of the platform for homing and calibration. Finally, all parts were attached to the main frame using 3D clamps made of PolyLactic Acid (PLA). With this configuration we achieve a horizontal resolution of 0.6 mm/step and a maximum operating speed of 27.3 mm/s.

Our shape generator is a motorized device that moves the pins in their vertical axis (up/down). It contains 10 custom push-pull modules, each able to simultaneously drive two pins (Figure 5). All 10 modules are mounted adjacent to each other on an acrylic platform attached to the moving rail and can therefore simultaneously actuate all the 20 pins of a single row. The pushing is achieved via a rack and pinion mechanism paired with reduction geared DC motors (IG30-MM8.6W-E, 12 V, 800 mA). Vertical positioning works by placing 12 small neodymium magnets (ø2 x 1 T) inside the rack at distances of 1.5cm, sensed by a Hall sensor (WSH138-XPAN2) to close the loop. Conversely, the pulling mechanism was implemented using an electromagnet (25 N pulling force at 12 V, 260 mA) placed on the top of the the rack. When the electromagnet is in contact with the the bottom part of the pin (where the iron plate is attached), it turns on and the DC motor drives back the rack downward. All electronic parts of each module (5V regulator, H-bridges, LEDs, home switch, and an Arduino Nano) are soldered on a custom printed circuit board and powered by a five parallel power supplies (LRS-350-12, 12 V, 145 A).

4.3 Locking System

The purpose of our locking system is to firmly secure the pins at a specific height, so as to form the desired shape of the terrain and also to allow users to walk over the resulting terrain. The main challenge is the large number of pins, all of which require to be locked. To address this, we built a modular locking mechanism that can handle 80 pins (four rows) with just two servomotors (HS-311 with 5 V, 650 mA) and four aluminum pipes (800 mm, ø5). The system works by simultaneously sliding one pipe into the notches of all the pins placed along the same row, effectively locking these and preventing any vertical translation (Figure 8). To simplify our resulting device, we used two servomotors to drive simultaneously four pipes, hence simultaneously locking/unlocking four rows at a time. To cover all the 60 rows of Elevate, we replicated the aforementioned locking system 15 times along the longitudinal axis of the platform.

More specifically, our locking mechanism is driven by a rack and pinion, with a pair of spur-gears mounted on the shafts of the motors, and a linear gear serving as a rack, which connects the four pipes together. This allows for a 10mm displacement, sufficient for locking and unlocking all pins in a row. All parts were 3D printed using PLA. The locking system is controlled using an Arduino UNO and two servo drivers (PCA9685), and communicates with the computer via serial. A 5 V power supply (LRS-100-5, max 18 A) was used to provide sufficient wattage for all the motors.

4.4 Software Control

Elevate is controlled by the interactive application software, typically running on a desktop computer (e.g., for VR, etc). Our software operates at three distinct layers: application, communication, and

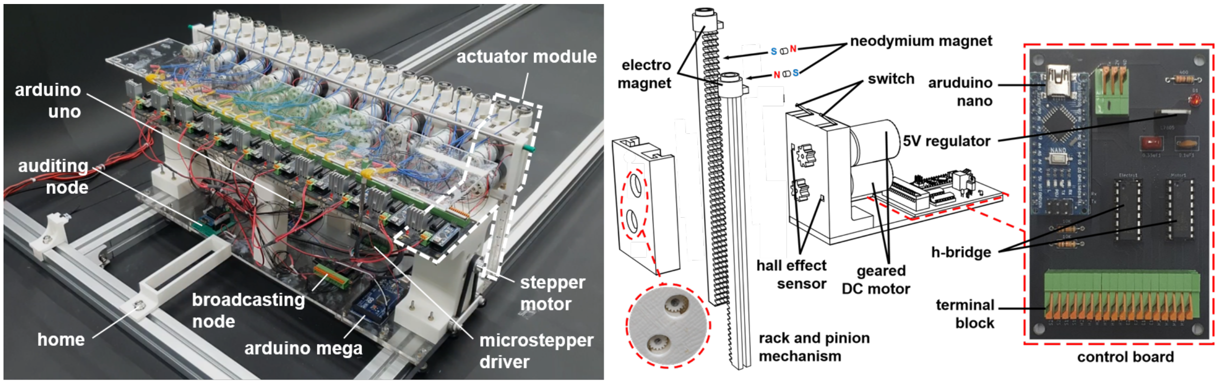

Figure 5: Hardware components of the shape generating system: overview of shape generator (left); hardware components of the custom actuator module (right).

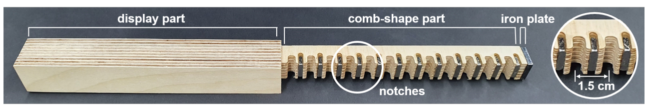

Figure 6: One of Elevate's pins. Note the different parts that comprise its mechanics, from left to right: (1) a display part, which extrudes out of the platform; (2) a comb-shaped part with notches that lock; (3) an iron plate at its base.

firmware. This hierarchical structure, which is depicted in Figure 7, provides an abstraction that allows for reusing parts of the system, and for decoupling the development of hardware and software.

The **application layer** is responsible of generating a 20 by 60 map containing the height position of each individual pin. This map is then internally stored as a JSON object, ready to be transmitted to the hardware. The details of the map-generation process are application-dependent and are described in the *Applications* section. Applications can be written in any language or with any software platform as long as they can create a JSON file — for example, we describe VR applications that were built using C# with Unity3D, and a mini-golf authoring tool that was built using Javascript and runs in a browser.

The **communication layer** is responsible of timing and dispatching the instructions to the hardware's individual parts (shape generator and locking system). All maps from the application layers are stored in a queue, and rendered as soon as the hardware is available. Maps can be added to the queue, or can replace those already in the queue. Once the hardware is ready to receive commands, the software creates a series of instructions describing how to actuate the 10 modules of the shape generator (a single row). Each instruction consists of a JSON string with the numerical ID of the target module and the height of its two pins. Specifically, it contains both the current and target positions of the pins, from which the firmware software can compute the difference of how much to push or pull. These JSON packets are transmitted over serial to the hardware.

Specifically, the communication layer is responsible for instructing the shape generator when and where to move (i.e., it follows the disk scheduling algorithm [39]), when to unlock the pins, when/how much to push or pull, and when to lock the pins again. These components of our software are structured as a closed-loop, as horizontal movements are restrained until all the racks on the actuator modules are down and click the homing switch (Figure 5, right). Furthermore, the controlling software internally keeps track of the current configuration of pins (e.g., the previous map), and instructs the hardware to skip rows that do not require changes, resulting in saved time.

Down at the hardware, our **communication layer** provides a serial channel between a PC and the Arduino Uno that manages the locking system. Furthermore we included a second serial channel between the PC and an Arduino Mega, which communicates with two Complex Programmable Logic Devices (CPLD, a device akin to an FPGA) on the shape generator. Our first CPLD serves as a signal multiplexer: it takes as input one transmission line and duplicates it for each of the the 10 receiving modules. Meanwhile, our second CPLD acting as an auditing node, collects the signal from all twenty switches at the actuator modules and checks for successful homing of the actuators. The CPLDs (using an Altera EPM3064ALC44-10) were programmed in Verilog.

On the lowest hardware level, the **firmware layer** consists of the individual programs that run on each microcontroller, all together controlling the horizontal moving platform, as well as the locking system. Each firmware independently handles: actuating the motors for the horizontal movement or locking/unlocking the pins; pushing and pulling the pins, position tracking via magnetic encoding, turning on/off the pulling electromagnet; checking for pins or device homing.

4.5 Technical evaluation and prototype limitations

We performed a series of tests aimed at measuring the accuracy and the time required for rendering a synthetically generated terrain on our Elevate haptic floor. As shown in 9, we constructed terrains resembling stairs from level 0 to level 10 (15 cm); these were chosen as they allow for quick manual inspection and enumeration of mistakes. Specifically, the stairs were constructed so that each row contained pins placed one level higher than the previous, and, once reached level 10, they fold back to level 0. Starting points were

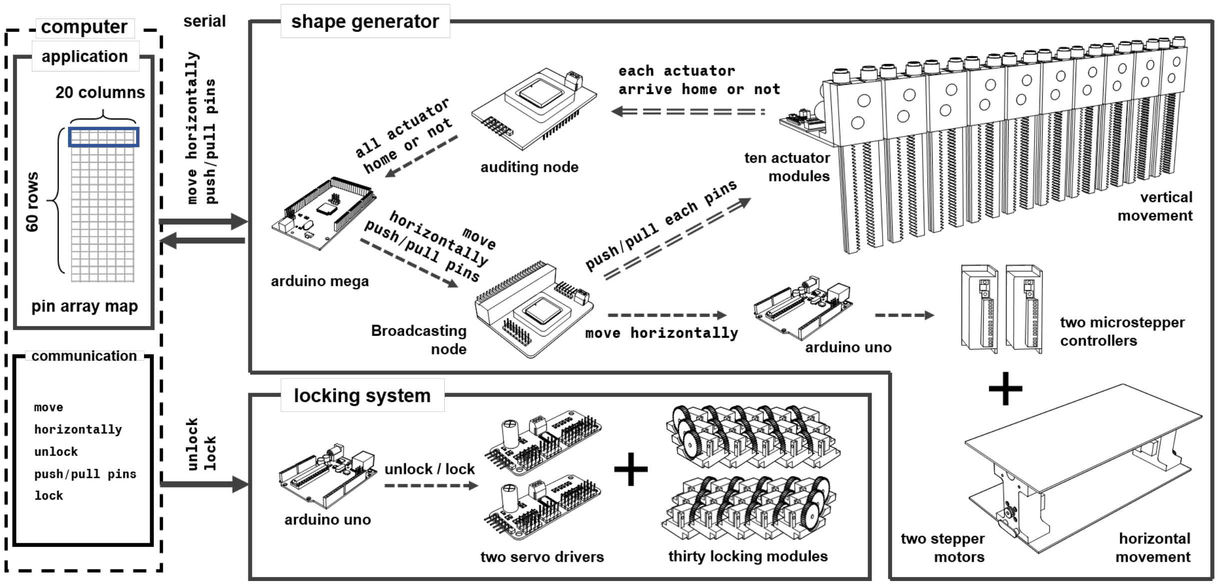

Figure 7: Overview of the software implementation used to control Elevate from a variety of different applications.

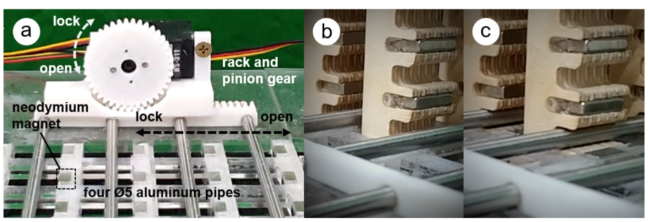

Figure 8: The locking module (a), pins are released (b), pins are locked (c).

Figure 9: Consecutively ascending pins to measure the error rate of entire pins

set randomly, so that none of the terrains tested were equal. We recorded the number of incorrect pin placements and the total rendering time by conducting 10 full cycles.

We found an average of 3.9 pins (SD: 2.64) that incorrectly rendered, leading to an accuracy of 99.7% (SD=0.22). These rare failures were caused by the pin dropping down before the locking system was able to activate. We measured 2.9 seconds for the shape-generator to push a row (when max height), and 1.1 seconds to move to the next row, resulting in a total of 4 minutes for rendering the full height terrain. Furthermore, a single pin without the locking system can endure up to a mean force of 6.98 N (N = 100, SD = 1.43), relying on temporal locks with magnets (forces measured with a digital force gauge, SHIMPO FGJN-5).

From these results, we shined some light also on our device's key limitations. Its main implementation is that it leverages a single shape-generator to render the complete haptic floor, by moving across the platform, row by row. While this design is cost-effective, by requiring a relatively small number of actuators for controlling a large amount of pins (a ratio 1:60), it is also inherently slow, as only pins placed on the same row can be controlled at the same time.

Nevertheless, these limitations can be circumvented with the appropriate interaction techniques at the application level. For example, it is not necessary to dynamically reconstruct a terrain with a high refresh rate: instead, the application designer can choose to actuate only small portions of the platform to render the interactive elements that change more often. Our *stepping-stones* application, described before, uses this mechanism: each rock thrown from the cliff only requires on average 30 s for rendering. Furthermore, the application designer can leverage on the tracking system and Elevate's large surface area to selectively update only the parts of the platforms where the user is not standing; in fact previous haptic floors, such as TilePop, also use these techniques to keep the user engaged while the device is updating [40]. In the next sections we describe a set of applications aimed to explore these techniques, and a user study for measuring the impact of these system's limitations over the user's sense of realism and enjoyment.

5 APPLICATIONS

To further showcase a wide range of uses of our device, we implemented four distinct applications: three virtual reality applications, and one stand-alone application that makes use of dynamic terrains.

5.1 Landscape

We developed a landscape application where users can experience immersive places with various terrains in VR. As depicted in Figures 1, 3, and 10, users can feel the ground level difference of hills and texture of stones in VR with their feet. The user can have uninterrupted seamless experience on the terrain while Elevate is partially generating terrains.

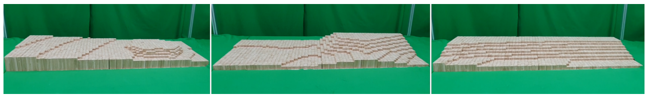

Figure 10: Various terrain spots on Landscape application

For this application, we reproduce the surface of a virtual environment in the Unity 3D game engine via scripts that check the height of all objects on a "Floor" layer. For each pin, we cast a ray downwards on the environment, and the layer masking enables the selective rendering of objects by the designer, for example rendering rocks and terrain, but not a snowball rolling through the environment. Designers have the option to let the environment be static or dynamic, and control the refresh rate of the floor, which is bounded by the speed at which the device can update a section.

As a user may damage the actuator if pins are raised while they stand over them, the script additionally allows the designer to dynamically mask a certain distance (mapped to rows) around a set of targets such as the user's feet. This creates a "dead zone", which does not get updated from the previous frame, making the actuator avoid the user's space and a potential damage. A VIVE controller is attached to a corner of the Elevate pins to align the virtual environment with the physical display. Two VIVE trackers are used to track the user's feet as they walk in virtual reality.

5.2 Stepping Stones

While the landscape application generates static and continuous topology, the stepping stone application sets up an interactive experience with a dynamic terrain that re-configures over time. The user can interact by grabbing and throwing off a cliff some grey colored stones. The purpose of this is to build a bridge that would allow to cross the canyon — a gap of 1.2m on the platform. When a thrown stone hits the bottom of the canyon, it starts to slowly rise up from the collided point. While it is lifting up, the shape generator forms the wooden pins according to the expected stone position in the VR environment. When the shape generator finishes the terrain, then the texture of the stone changes just like the other rocks within the VR environment, informing the user that the stone is ready to step on.

5.3 Stairs

The stairs application allows users to build various kinds of stairs in the VR environment, providing adjustable parameters (width, length, height, number of steps) and different types of stairs configurations, e.g., ascending, descending, u-shaped, mountain-shaped, and valley shaped configurations (Figure 12). Users can then wholly experience climbing a ramp of stairs, or sitting on its steps. This gives to the users not only a visual but also the haptic experience of height. Finally the users can dynamically design new stairs and adjust its parameters, so to physically experience in almost real-time the results of new architectural configurations.

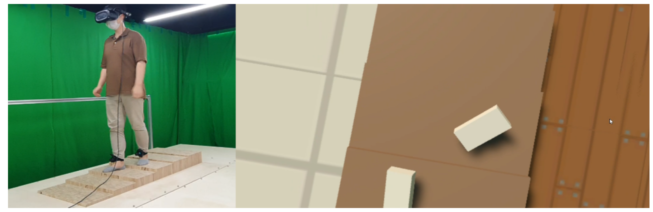

Figure 11: Descending from the Stair application in VR with VIVE trackers (left), the user's perspective of view—the blocks represent user's feet (right).

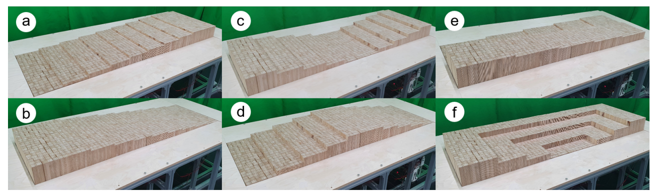

Figure 12: Six possible examples of stairs: (a),(b) straight ascending and descending; (c) valley shaped; (d) mountain shaped; (e) u-shaped; (f) amphitheatre shaped.

5.4 Golf

Beyond VR, this application demonstrates playing a mini-golf in the real physical world, in which the floor provides a dynamic terrain for a physical golf ball to roll on. The users can design various terrain patterns for mini-golf using an authoring web-based graphical interface. With this, they can select individual pins and directly adjust their heights, or they can use pattern brushes with an adjustable radius to quickly render linear or curved hills, holes, slopes, and rocky textures. Map designers can also modify the depth and the rotation of each of these brushes. Finally, they can save a sequence of terrain patterns as an animation that the hardware system will playback in a loop. As a result, shown in Figure 13, users can create an obstacle that elevates dynamically to challenge the player.

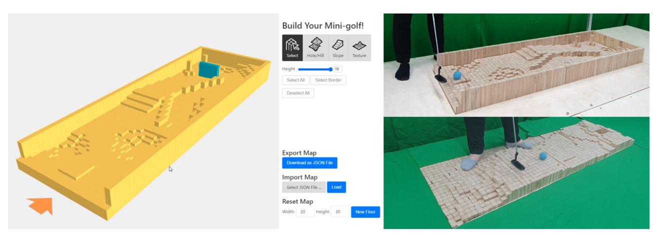

Figure 13: The web application to design the mini-golf field (left), playing the dynamic mini-golf application (right).

6 USER STUDY

We conducted a user study to investigate the perceived realism and enjoyment of walking over our device, as it rendered different types of terrains for virtual reality.

6.1 Study design

Our study followed a within-subjects design with a single modality factor: **haptic** (our device) vs. **no-haptic experience** (baseline condition). In the haptic condition, the participants walked in a VR simulation with terrains rendered using the Elevate system, while in the no-haptic case, the users walked on the flat wooden platform (i.e., pins did not actuate).

Specifically, we utilized two of the applications described in the previous section (*stepping stone* and *landscape*) and stitched them together in a single coherent VR experience. We did so to allow participants to be immersed in a single VR scene that allows them to experience both dynamic elements of the terrain (the stepping stones), and large detailed features of the landscape. The application switching was scripted as part of the experience, with users required to briefly look at the sky after having crossed the canyon — an expedient needed to render the incoming terrain. By design, this change of scenery required users to remain still while looking around, waiting for the terrain to be reshaped. This, purposely, allowed us to investigate whether a forced pause during the application would disrupt the enjoyment of the VR experience.

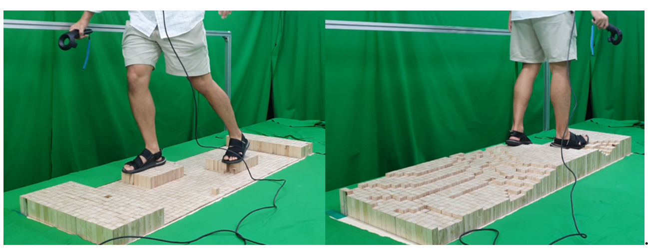

Figure 14: A participant experiencing terrains during the experiment; on the left we depict a scene from our stepping stone VR application; while on the right a scene from our landscape VR application.

6.2 Hypotheses

Our main hypothesis was that experiencing the VR environment by walking on top of our haptic floor would create a higher sense of realism than in the baseline condition **(H1)**. Secondly, we postulated that experiencing the VR environment by walking on our haptic floor would be more enjoyable for participants than the baseline condition **(H2)**.

6.3 Participants

We recruited eight participants from our local institution (two females, and six males) aged 23-39 years old (M=28.5, SD=4.72) and of body weight between 60.1 - 79 Kg (M: 71.7, SD=6.70). Three participants reported being familiar with both VR and haptic devices, while two others reported familiarity with one of the two. Participants were compensated with 10 USD in local currency for their time.

6.4 Procedure

After completing a demographics intake form, participants were asked to experience the applications (for at least 5 minutes) in both conditions (haptic vs. visual-only) following previous research [13, 16, 17]. The order of conditions was fully counterbalanced.

For the whole duration of each condition, participants wore an HTC Vive Cosmos Elite VR headset and their own shoes. Participants were instructed that they could terminate the experiment at any time, and that, for safety measures, they had to turn around and wait outside of the actuated platform while the terrain was regenerated.

An experimenter was present next to the participants all the time for safety. After each condition, the participants were asked to rate the perceived realism and enjoyment on a 7-point Likert scale (as in [13, 17]) for each part of the application (stepping stones and landscape). Before concluding the study, we also conducted a semi-structured interview aiming to extract qualitative observations and comments about their experience. The experiment took in total about 40 minutes to complete.

6.5 Results

Figure 15 shows the subjective assessment of realism and enjoyment for both conditions. Results were analyzed using Friedman test followed by post-hoc pairwise analysis with Wilcoxon signed-rank test ($\alpha = 0.05$). We report statistically significant differences between the baseline and haptic conditions for both realism ($X^2(2) = 21.000, p < 0.001$) and enjoyment ($X^2(2) = 18.280, p < 0.001$). The post-hoc analysis further reveals that the haptic condition was rated significantly better than the baseline regardless of the stage of the application, for both realism (landscape: $Z = -2.527, p = 0.012$, stepping stones: $Z = -2.536, p = 0.011$) and enjoyment (landscape: $Z = -2.386, p = 0.017$, stepping stones: $Z = -2.536, p = 0.011$); respectively, these findings support our H1 and H2.

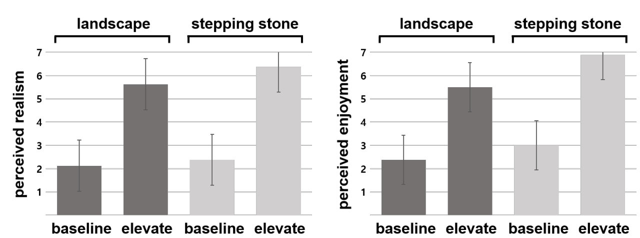

Figure 15: Participant's perceived realism and enjoyment in the application for baseline and elevate condition. We found that elevate improves both metrics. The error-bar represents a 95% of confidence interval.

6.6 Qualitative findings

The qualitative findings that emerged from the interviews with our participants further corroborate our previous results. All participants agreed that the VR experience using Elevate felt more realistic and enjoyable, and, as a result, more immersive. For instance, P2 stated, "Experiencing the [stepping] stones was fascinating", while others described it as "amazing" (P5) and "fun" (P6). When asked to comment on what they appreciated the most, P3 remarked that "It was nice to experience the height and slope changes while I walk[ed] on the landscape." Participants also commented about the resolution of the terrain's details, reporting to be satisfied with it. P3 described being able "to feel the geometry of the stone with my foot", and P2 and P8 of being able to perceive terrains inclinations: "My ankles were tilted due to the slope [...] so I felt the height and the slope very clearly" (P2). Some other participants, on the contrary, expressed limitations regarding the resolution of details in the landscape application, commenting that "the slope difference was not that clear" (P4) and that the resolution of curved objects was "a bit disappointing" (P6), but nonetheless was felt more realistic than in the visual-only condition. Additionally, participants reported that they felt confident in walking across the device. Five participants reported that the device felt "solid" (P5, P7) and that they trusted the locking mechanisms (P4, P6, P8).

When asked which part of the VR application participants preferred, all participants agreed that the stepping stone was more enjoyable than the landscape; this was unsurprising as it contained more drastic physical elevations. P2, P5, and P6 responded that it was more realistic and enjoyable because they could feel the "extreme reality of a cliff with their toes". P1 and P7 mainly appreciated the game dynamics of the application, such as throwing stones and stepping on them: "grabbing and throwing the stone, and watching the stone lifting up slowly made me the entire experience pleasurable" (P3). Realism also played an important role, as participants felt more *scared* about being on the edge of a cliff: "I was extremely horrified when I moved closer to the cliff edge. I truly felt that I was this close to fall." (P4) and "I was much scared because I could feel the empty space with my feet."(P5).

Finally, when asked about what needs further improvements, all participants except one responded that they would like the terrain generator to act faster. Indeed, they remarked that the pause between the stitched applications felt "long" and "boring". P2, who did not feel bored, commented that "I didn't feel bored when the pins were transitioning (...) I was watching and observing the other parts of the scene". This comment suggests opportunities for designing entertaining expedients while participants are required to wait for parts of the terrain to reshape; similar to what previous slow haptic displays, such as TilePoP [40] implemented to engage their users while waiting for the device to refresh (5-20 seconds needed). Finally, unsurprisingly, five participants (P2, P3, P4, P6, P8) requested that the terrain be made even larger, and with even higher resolution: "[the resolution] was enough for wearing shoes, but it is not enough for barefoot" (P3). The next section of this paper follows up this list of limitations and describes opportunities for future improvements.

7 DISCUSSION AND FUTURE WORK

Our user study has established the benefits of how the device adds to immersive experience in VR environment. However, there are limitations and possible avenues for improvements. First, the main issue raised in the study was, as expected, the refresh rate of our current implementation. While quick terrain updates, such as the appearance of a stone in the VR canyon, did not disturb the sense of immersion, the same was not true for longer updates that reconfigured the entire area; here, our participants had to wait. To solve this issue, one can either increase the number of actuators in the device or add a secondary shape generator to halve the transformation time. Secondly, participants requested a wider terrain area. This can be improved by extending the pin rows, which does not increment the cost proportionately to the number of pins since its sharing the same shape generator. Also, terrains can be "virtually" extended using space-folding and redirecting techniques as shown in previous work [19, 34]. Third, few participants raised the issue of limited pin height resolution, we agree that the higher resolution and the pin height would expand the rendering spectrum, however, our pin height (3×3×15 cm, 10 steps with 1.5cm/step) is chosen in consideration of the height of the device, the weight of the material, the user, and the resulting cost. Compared to previous research, our pins are smaller but longer ([16]: 5×5×10 cm), and more importantly, each pin can support the full weight of a user. Lastly, we explicitly did not set any restrictions on participants' shoes, hoping to show Elevate's applicability to real-case scenarios. However, different shoes may affect the haptics on the feet. Indeed, our study, despite being agnostic of the shoes' sole, demonstrates that the perceived realism has increased for the Elevate condition compared to VR on a flat surface.

For future work, we plan to investigate the perception on human-navigation on a pin-array terrain, and thresholds of a pin size and heights of the pin-array display. We also plan to develop applications based on haptic illusion like in [19, 20, 26, 34] to extend the potential usage of the device and accomplish *real-walking* VR experience [3, 4, 45, 49]. Regarding the technical work, we will improve the hardware to achieve different means of interactions. For example, by changing the size of the pins, we could render furniture and provide whole-body interactions as in [35, 36, 40]. Also, mobilizing the pin-array terrain [10, 31] would allow to cover larger VR environment without scaling the number of pins. Finally, additional features such as sensing pressure, controlling stiffness, and actuating vibro-tactile motors could be employed to enhance various interactions, similarly to [21, 22, 44, 48].

8 CONCLUSION

In this paper, we introduced Elevate a walkable high-resolution pin-array display that can render a variety of physical terrains for VR simulations. Elevate has four key characteristics that distinguish it from other previous works: 1) it withstands human weights; 2) its feedback is dynamic; 3) it is a large walkable surface; 4) it has an unprecedented resolution of 1,200 pins. To show the design space of Elevate we then designed a set of VR and phsyical applications (landscape; stepping stone; stairs; and non-VR mini-golf) which demonstrates how designers can take advantage of the system's unique capabilities and avoid some of the inherent limitations. Finally, though a user study with eight participants, we showed that Elevate provides a richer degree of realism and immersion, resulting in measurable increase of enjoyment of walkable VR experiences.

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REFERENCES

[1] Laroussi Bouguila, Béat Hirsbrunner, Makoto Sato, and Masaru Iwashita. 2003. Virtual Locomotion Interface with Ground Surface Simulation.. In *ICAT.*

[2] Nicolas Bouillot and Micha Seta. 2019. A Scalable Haptic Floor dedicated to large Immersive SpaceWohlaufs. In *Proceedings of the 17th Linux Audio Conference (LAC-19), CCRMA, Stanford University, USA (2019)*, Vol. 5.

[3] Elodie Bouzbib, Gilles Bailly, Sinan Haliyo, and Pascal Frey. 2020. CoVR: A Large-Scale Force-Feedback Robotic Interface for Non-Deterministic Scenarios in VR. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '20)*. Association for Computing Machinery, New York, NY, USA, 209–222. https://doi.org/10.1145/3379337.3415891

[4] Lung-Pan Cheng, Thijs Roumen, Hannes Rantzsch, Sven Köhler, Patrick Schmidt, Robert Kovacs, Johannes Jasper, Jonas Kemper, and Patrick Baudisch. 2015. TurkDeck: Physical Virtual Reality Based on People. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* (Charlotte, NC, USA) *(UIST '15)*. Association for Computing Machinery, New York, NY, USA, 417–426. https://doi.org/10.1145/2807442.2807463

[5] Imre Cikajlo, Jakob Oblak, and Zlatko Matjačić. 2011. Haptic floor for virtual balance training. In *2011 IEEE world haptics conference*. IEEE, 179–184. https://doi.org/10.1109/WHC.2011.5945482

[6] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. inFORM: Dynamic Physical Affordances and Constraints through Shape and Object Actuation *(UIST '13)*. ACM Press, 417–426. https://doi.org/10.1145/2501988.2502032

[7] Erik Hill, Hiroyuki Hatano, Masahiro Fujii, and Yu Watanabe. 2014. Haptic foot interface for language communication. In *Proceedings of the 5th Augmented Human International Conference*. 1–4. https://doi.org/10.1145/2582051.2582060

[8] John Hollerbach, David Grow, and Craig Parker. 2005. Developments in locomotion interfaces. In *9th International Conference on Rehabilitation Robotics, 2005. ICORR 2005.* IEEE, 522–525. https://doi.org/10.1109/ICORR.2005.1501156

[9] Ryuta Ishikawa, Akifumi Inoue, and Tohru Hoshi. 2018. Investigating perceived slope gradient in virtual environment with visuo-haptic interaction. In *Proceedings of the 30th Australian Conference on Computer-Human Interaction*. 559–562. https://doi.org/10.1145/3292147.3292234

[10] Hiroo Iwata, Hiroaki Yano, Hiroyuki Fukushima, and Haruo Noma. 2005. CirculaFloor [locomotion interface]. *IEEE Computer Graphics and Applications* 25, 1 (2005), 64–67. https://doi.org/10.1109/MCG.2005.5

[11] Hiroo Iwata, Hiroaki Yano, and Fumitaka Nakaizumi. 2001. Gait master: A versatile locomotion interface for uneven virtual terrain. In *Proceedings IEEE Virtual Reality 2001.* IEEE, 131–137. https://doi.org/10.1109/VR.2001.913779

[12] Hiroo Iwata, Hiroaki Yano, Fumitaka Nakaizumi, and Ryo Kawamura. 2001. Project FEELEX: Adding Haptic Surface to Graphics. In *Proceedings of the 28th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '01)*. Association for Computing Machinery, New York, NY, USA, 469–476. https://doi.org/10.1145/383259.383314

[13] Seungwoo Je, Myung Jin Kim, Woojin Lee, Byungjoo Lee, Xing-Dong Yang, Pedro Lopes, and Andrea Bianchi. 2019. Aero-plane: A Handheld Force-Feedback Device that Renders Weight Motion Illusion on a Virtual 2D Plane. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. 763–775. https://doi.org/10.1145/3332165.3347926

[14] Narae Lee, Ju-Whan Kim, Jungsoo Lee, Myeongsoo Shin, and Woohun Lee. 2012. MoleBot: a robotic creature based on physical transformability. In *Proceedings of the 2012 Virtual Reality International Conference*. 1–4. https://doi.org/10.1145/2331714.2331734

[15] Daniel Leithinger, Sean Follmer, Alex Olwal, Samuel Luescher, Akimitsu Hogge, Jinha Lee, and Hiroshi Ishii. 2013. Sublimate: State-Changing Virtual and Physical Rendering to Augment Interaction with Shape Displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. Association for Computing Machinery, New York, NY, USA, 1441–1450. https://doi.org/10.1145/2470654.2466191

[16] Daniel Leithinger, David Lakatos, Anthony DeVincenzi, Matthew Blackshaw, and Hiroshi Ishii. 2011. Direct and Gestural Interaction with Relief: A 2.5D Shape Display. In *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology (UIST '11)*. Association for Computing Machinery, New York, NY, USA, 541–548. https://doi.org/10.1145/2047196.2047268

[17] Pedro Lopes, Sijing You, Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch. 2017. Providing Haptics to Walls & Heavy Objects in Virtual Reality by Means of Electrical Muscle Stimulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 1471–1482. https://doi.org/10.1145/3025453.3025600

[18] Maud Marchal, Gabriel Cirio, Yon Visell, Federico Fontana, Stefania Serafin, Jeremy Cooperstock, and Anatole Lécuyer. 2013. Multimodal rendering of walking over virtual grounds. In *Human Walking in Virtual Environments*. Springer, 263–295. https://doi.org/10.1007/978-1-4419-8432-6_12

[19] Keigo Matsumoto, Yuki Ban, Takuji Narumi, Yohei Yanase, Tomohiro Tanikawa, and Michitaka Hirose. 2016. Unlimited Corridor: Redirected Walking Techniques Using Visuo Haptic Interaction. In *ACM SIGGRAPH 2016 Emerging Technologies* (Anaheim, California) *(SIGGRAPH '16)*. Association for Computing Machinery, New York, NY, USA, Article 20, 2 pages. https://doi.org/10.1145/2929464.2929482

[20] Ryohei Nagao, Keigo Matsumoto, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose. 2017. Infinite stairs: simulating stairs in virtual reality based on visuo-haptic interaction. In *ACM SIGGRAPH 2017 Emerging Technologies*. 1–2. https://doi.org/10.1145/3084822.3084838

[21] Ken Nakagaki, Daniel Fitzgerald, Zhiyao Ma, Luke Vink, Daniel Levine, and Hiroshi Ishii. 2019. inFORCE: Bi-directionalForce'Shape Display for Haptic Interaction. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*. 615–623. https://doi.org/10.1145/3294109.3295621

[22] Ken Nakagaki, Yingda Liu, Chloe Nelson-Arzuaga, and Hiroshi Ishii. 2020. TRANS-DOCK: Expanding the Interactivity of Pin-based Shape Displays by Docking Mechanical Transducers. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*. 131–142. https://doi.org/10.1145/3374920.3374933

[23] Niels Christian Nilsson, Stefania Serafin, Frank Steinicke, and Rolf Nordahl. 2018. Natural walking in virtual reality: A review. *Computers in Entertainment (CIE)* 16, 2 (2018), 1–22. https://doi.org/10.1145/3180658

[24] H. Noma, T. Sugihara, and T. Miyasato. 2000. Development of Ground Surface Simulator for Tel-E-Merge System. In *Proceedings IEEE Virtual Reality 2000 (Cat. No.00CB37048)*. 217–224. https://doi.org/10.1109/VR.2000.840501

[25] Ivan Poupyrev, Tatsushi Nashida, and Makoto Okabe. 2007. Actuation and Tangible User Interfaces: The Vaucanson Duck, Robots, and Shape Displays. In *Proceedings of the 1st International Conference on Tangible and Embedded Interaction (TEI '07)*. Association for Computing Machinery, New York, NY, USA, 205–212. https://doi.org/10.1145/1226969.1227012

[26] Sharif Razzaque. 2005. *Redirected Walking*. Ph.D. Dissertation. USA. Advisor(s) Brooks, Fredrick P.

[27] AF Rovers and HA Van Essen. 2006. Guidelines for haptic interpersonal communication applications: an exploration of foot interaction styles. *Virtual Reality* 9, 2-3 (2006), 177–191. https://doi.org/10.1007/s10055-005-0016-0

[28] Dominik Schmidt, Rob Kovacs, Vikram Mehta, Udayan Umapathi, Sven Köhler, Lung-Pan Cheng, and Patrick Baudisch. 2015. Level-ups: Motorized stilts that simulate stair steps in virtual reality. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 2157–2160. https://doi.org/10.1145/2702123.2702253

[29] Dominik Schmidt, Raf Ramakers, Esben W Pedersen, Johannes Jasper, Sven Köhler, Aileen Pohl, Hannes Rantzsch, Andreas Rau, Patrick Schmidt, Christoph Sterz, et al. 2014. Kickables: tangibles for feet. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 3143–3152. https://doi.org/10.1145/2556288.2557016

[30] Henning Schmidt, Stefan Hesse, Rolf Bernhardt, and Jörg Krüger. 2005. HapticWalker—a novel haptic foot device. *ACM Transactions on Applied Perception (TAP)* 2, 2 (2005), 166–180. https://doi.org/10.1145/1060581.1060589

[31] Alexa F. Siu, Eric J. Gonzalez, Shenli Yuan, Jason B. Ginsberg, and Sean Follmer. 2018. ShapeShift: 2D Spatial Manipulation and Self-Actuation of Tabletop Shape Displays for Tangible and Haptic Interaction. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3173865

[32] Hyungki Son, Hyunjae Gil, Sangkyu Byeon, Sang-Youn Kim, and Jin Ryong Kim. 2018. Realwalk: Feeling ground surfaces while walking in virtual reality. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–4. https://doi.org/10.1145/3170427.3186474

[33] Toshiaki Sugihara and Tsutomu Miyasato. 1998. The terrain surface simulator ALF (Alive! Floor). *Proc. of VRSJ ICAT'98* (1998), 170–174.

[34] E. A. Suma, Z. Lipps, S. Finkelstein, D. M. Krum, and M. Bolas. 2012. Impossible Spaces: Maximizing Natural Walking in Virtual Environments with Self-Overlapping Architecture. *IEEE Transactions on Visualization and Computer Graphics* 18, 4 (2012), 555–564. https://doi.org/10.1109/TVCG.2012.47

[35] Ryo Suzuki, Hooman Hedayati, Clement Zheng, James L Bohn, Daniel Szafir, Ellen Yi-Luen Do, Mark D Gross, and Daniel Leithinger. 2020. RoomShift: Room-scale Dynamic Haptics for VR with Furniture-moving Swarm Robots. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–11. https://doi.org/10.1145/3313831.3376523

[36] Ryo Suzuki, Ryosuke Nakayama, Dan Liu, Yasuaki Kakehi, Mark D. Gross, and Daniel Leithinger. 2020. LiftTiles: Constructive Building Blocks for Prototyping Room-Scale Shape-Changing Interfaces. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '20)*. Association for Computing Machinery, New York, NY, USA, 143–151. https://doi.org/10.1145/3374920.3374941

[37] Ryo Suzuki, Junichi Yamaoka, Daniel Leithinger, Tom Yeh, Mark D. Gross, Yoshihiro Kawahara, and Yasuaki Kakehi. 2018. Dynablock: Dynamic 3D Printing for Instant and Reconstructable Shape Formation. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 99–111. https://doi.org/10.1145/3242587.3242659

[38] Yuichiro Takeuchi. 2010. Gilded gait: reshaping the urban experience with augmented footsteps. In *Proceedings of the 23nd annual ACM symposium on User interface software and technology*. 185–188. https://doi.org/10.1145/1866029.1866061

[39] Andrew S. Tanenbaum and Herbert Bos. 2014. *Modern Operating Systems* (4th ed.). Prentice Hall Press, USA.

[40] Shan-Yuan Teng, Cheng-Lung Lin, Chi-huan Chiang, Tzu-Sheng Kuo, Liwei Chan, Da-Yuan Huang, and Bing-Yu Chen. 2019. TilePoP: Tile-Type Pop-up Prop for Virtual Reality. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology (UIST '19)*. Association for Computing Machinery, New Orleans, LA, USA, 639–649. https://doi.org/10.1145/3332165.3347958

[41] Luca Turchet, Paolo Burelli, and Stefania Serafin. 2012. Haptic feedback for enhancing realism of walking simulations. *IEEE transactions on haptics* 6, 1 (2012), 35–45. https://doi.org/10.1109/TOH.2012.51

[42] Yon Visell and Jeremy R Cooperstock. 2010. Design of a vibrotactile display via a rigid surface. In *2010 IEEE haptics symposium*. IEEE, 133–140. https://doi.org/10.1109/HAPTIC.2010.5444664

[43] Yon Visell, Jeremy R Cooperstock, Bruno L Giordano, Karmen Franinovic, Alvin Law, Stephen McAdams, Kunal Jathal, and Federico Fontana. 2008. A vibrotactile device for display of virtual ground materials in walking. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 420–426. https://doi.org/10.1007/978-3-540-69057-3_55

[44] Yon Visell, Alvin Law, and Jeremy R Cooperstock. 2009. Touch is everywhere: Floor surfaces as ambient haptic interfaces. *IEEE Transactions on Haptics* 2, 3 (2009), 148–159. https://doi.org/10.1109/TOH.2009.31

[45] Yuntao Wang, Zichao (Tyson) Chen, Hanchuan Li, Zhengyi Cao, Huiyi Luo, Tengxiang Zhang, Ke Ou, John Raiti, Chun Yu, Shwetak Patel, and Yuanchun Shi. 2020. MoveVR: Enabling Multiform Force Feedback in Virtual Reality Using Household Cleaning Robot. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376286

[46] Yue Wang and Mark A Minor. 2014. Design of a bladder based elastomeric Smart Shoe for haptic terrain display. In *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 1236–1241. https://doi.org/10.1109/IROS.2014.6942715

[47] Anne Wohlauf, Fabian Hemmert, and Reto Wettach. 2017. The Haptic Body Scale: Designing Imprecision in Times of the Quantified Self. In *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction* (Yokohama, Japan) *(TEI '17)*. Association for Computing Machinery, New York, NY, USA, 367–373. https://doi.org/10.1145/3024969.3025003

[48] Xiao Xiao, Donald Derek Haddad, Thomas Sanchez, Akito van Troyer, Rébecca Kleinberger, Penny Webb, Joe Paradiso, Tod Machover, and Hiroshi Ishii. 2016. Kinéphone: Exploring the Musical Potential of an Actuated Pin-Based Shape Display.. In *NIME*. 259–264.

[49] Yan Yixian, Kazuki Takashima, Anthony Tang, Takayuki Tanno, Kazuyuki Fujita, and Yoshifumi Kitamura. 2020. ZoomWalls: Dynamic Walls That Simulate Haptic Infrastructure for Room-Scale VR World. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '20)*. Association for Computing Machinery, New York, NY, USA, 223–235. https://doi.org/10.1145/3379337.3415859

[50] Shigeo Yoshida, Yuqian Sun, and Hideaki Kuzuoka. 2020. PoCoPo: Handheld Pin-Based Shape Display for Haptic Rendering in Virtual Reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376358

[51] K. Zhang and S. Follmer. 2018. Electrostatic adhesive brakes for high spatial resolution refreshable 2.5D tactile shape displays. In *2018 IEEE Haptics Symposium (HAPTICS)*. 319–326. https://doi.org/10.1109/HAPTICS.2018.8357195